REPORT 538

REPORT 538

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

64 RUE DE VARENNE PARIS 7E FRANCE

Flight experience with the Ogee wing at low speed

by F.J.Drinkwater III and L.S.Rolls

★

MAY 1966

NORTH ATLANTIC TREATY ORGANIZATION

REPORT 538

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

FLIGHT EXPERIENCE WITH THE OGEE WING AT LOW SPEED

by

Fred J.Drinkwater III, and L.Stewart Rolls

Ames Research Center
Moffett Field, California, USA

This Paper was presented to the Flight Mechanics Panel of the Advisory Group for Aerospace Research and Development, Paris, France, May 10-13, 1966

SUMMARY

A basic delta-wing aircraft was modified to an Ogee plan form and tested in flight following full-scale wind-tunnel tests. The modified wing had a sharp leading edge compared to the original large-radius, slatted leading edge. The modification produced strong leading-edge vortices which were easily observed and photographed as condensation trails. The stability of the vortices was examined in flight to 25° angle of attack and 8° sideslip and no detachment of the vortices or other discontinuous characteristics were indicated. A significant improvement in lateral-directional stability over that of the basic airplane was obtained at high angles of attack, which allowed a reduction in the minimum instrument approach speed. The improved lateral-directional characteristics made it possible to extend to lower speeds the study of other piloting factors which might determine the minimum approach speed. The effects of a range of static margins from -0.02 to +0.02 were examined. Also, the effect of a change in the slope of the power-required curve, which was obtained by making landing approaches over a range of airspeeds, was investigated. Poor static longitudinal stability and reduced flight-path-angle control became the limiting factors.

RESUME

Un avion de base à aile en delta modifié suivant une forme en plan Ogee a subi des essais en vol à la suite d'essais vraie grandeur effectués en soufflerie. L'aile modifié possédait un bord d'attaque aigu par rapport au bord d'attaque initial à bec et à grand rayon. La modification a donné lieu à de forts tourbillons de bord d'attaque que l'on a facilement constatés et photographiés comme des traînees de condensation. La stabilité des tourbillons a été étudiée en cours de vol sous un angle d'attaque de 25° et un angle de dérapage de 8°; aucun détachement tourbillonnaire ni autres discontinuités n'ont été constatés. Une amélioration sensible de la stabilité latérale et directionnelle sur celle de l'avion de base a été obtenue à des angles d'attaque élevés, permettant ainsi une réduction de la vitesse minimum d'approche aux instruments. Les caractéristiques latérales et directionnelles améliorées ont rendu possible l'extension aux vitesses faibles de l'étude d'autres facteurs de pilotage susceptibles de déterminer la vitesse minimum d'approche. Les effets d'une gamme de marges statiques comprises entre -0,02 and 0,02 ont été examinés. En plus, l'influence d'une variation de la forme de la courbe de la puissance requise, obtenue en effectuant des approches d'atterrissage dans une gamme de vitesses, a été étudiée. Une stabilité longitudinale statique faible et une commande réduite de l'angle de la trajectoire sont devenues des facteurs limitants.

533.693.1:533.6.013.67

CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOTATION

C_D	drag coefficient
C_L	lift coefficient
$\bar{c}$	mean aerodynamic chord, ft
V_a	landing approach speed, knots
V_i	indicated air speed, knots
V_s	stalling speed, knots
W/S	wing loading, lb/ft^2
$\frac{\Delta T/W}{knot}$	slope of thrust required curve, lb/knot
α	angle of attack, deg
β	angle of sideslip, deg
δ_E	elevon deflection, deg
δ_R	rudder deflection, deg
$\dot{\phi}$	rolling velocity, rad/sec

FLIGHT EXPERIENCE WITH THE OGEE WING AT LOW SPEED

Fred J. Drinkwater III, and L. Stewart Rolls

1. INTRODUCTION

Wind-tunnel tests showed that relatively minor variations in wing plan form can significantly alter the aerodynamic characteristics of a basic delta wing. The tests also indicated that a wing design optimized for very high-speed flight would have desirable high lift characteristics that would permit low landing speeds. The reflexed Gothic or Ogee shape with a sharp leading edge appears particularly interesting because it induces strong leading-edge vortices which allow the wing to continue to develop lift at relatively high angles of attack. This configuration would have higher induced drag than a basic delta configuration, however, and would have a steeper slope to the power-required curve at landing-approach speeds. There is also the possibility that the leading-edge vortices may be unsteady and, since their influence on the dynamic stability of the airplane was not known, a flight program was undertaken to determine the extent to which they would limit the usefulness of the lower approach speeds. Full-scale wind-tunnel tests of a Douglas F5D-1 airplane modified to an Ogee plan form provided basic aerodynamic data and defined in more detail the configuration to be tested. The availability of an unmodified airplane allowed alternate flying of the two aircraft for subjective comparison.

It has been difficult to generalize the degree to which low-aspect-ratio delta-wing airplane characteristics limit low-speed operation or otherwise affect handling qualities. Therefore, the flight tests were extended to include the effects of variations in the slope of the power-required curve on the pilot's ability to fly the ILS, an evaluation of criteria to provide a landing reference airspeed in the absence of a well-defined stall, and the landing behavior of the airplane as it is influenced by ground effect. Lift and pitching-moment changes in ground effect were measured both in flight and in the Ames 40 by 80 ft Wind Tunnel.

2. TEST AIRCRAFT MODIFICATIONS

A Douglas F5D-1 airplane was modified to an Ogee plan form by moving the engine inlets forward and extending the leading edge as shown in Figure 1. The plan-form extension was tapered to a sharp leading edge replacing both the original large radius leading edge and the slat which had been located in the area shown in Figure 1.

The plan-form modification increased the wing area by 104 square feet; however, most of the wing-area increase indicated in Figure 1 is the result of the convention used to determine the wing areas. The weight of the aircraft varied from 25,000 to 21,000 pounds ($W/S = 37.8$ to $W/S = 31.5$) during the flight tests and the center of gravity was at $0.32\ \bar{c}$. Dimensional data for the basic and modified airplanes are listed in Table I.

3. INSTRUMENTATION

Recording instruments were installed to simultaneously record measurements of airspeed, altitude, normal and longitudinal acceleration, angles of attack and sideslip, and tail-pipe total pressure. Control position transducers were mounted at the control surfaces and angular turnmeters were installed to document the trim and stability characteristics and unsteady phenomena. To minimize the errors in the airspeed and angle-of-attack measuring systems, a boom 10 ft long was mounted on the nose of the aircraft. This installation was not calibrated, but a similar installation used in the tests[1] indicated the errors to be small.

A motion picture camera was mounted on the vertical tail to photograph the wing tufts and vortex patterns and a camera was mounted vertically under the fuselage for photographing the runaway to obtain height, height rate, and ground speed for ground effect measurements.

4. OGEE AIRPLANE CHARACTERISTICS

4.1 Vortex Flow Observations

The purpose of the initial flights was to establish the behavior of the leading-edge vortices. Rear view mirrors were mounted so that the pilot could see both leading edges and considerable wing area and so could observe the flow continuously. Photographs of the condensation trails (Figs. 2 and 3), which were visible in all but the dryest air, show that in steady flight the vortex core passes above the leading edge and at a higher sweep angle than that of the wing. The changes in the vortex characteristics due to both angle of attack and sideslip agree with those measured during water-tunnel tests on an Ogee plan form[2].

A set of sketches of the tuft patterns over the wing of the test airplane at various angles of attack are presented in Figure 4. The sketches were derived from photographs taken by the tail-mounted camera. The first three sketches show the increase in the area of unsteady flow on the wing as the angle of attack changes from 7.5^{o} to 15^{o} and then to 18^{o}. The two sketches at 18^{o} angle of attack show the variation in tuft patterns during the mild buffet onset portion of flight and represent an increase in the area of unsteady flow in Figure 4(d). Since the tuft patterns changed between that in Figures 4(c) and (d) (about every 0.3 second), it was reasoned that the flow changes over the outboard section of the wing might be one of the causes of the mild lateral disturbance noted at angles of attack greater than 15^{o}. At about 15^{o} angle of attack on both the Ogee and basic airplane, a mild self-induced lateral disturbance occurred which would be referred to as stall warning or pre-stall buffet on most airplanes. The tuft flow shown in Figure 4 and visual observations of the tuft reaction in flight indicate that flow separation is occurring on the wing tips outboard of the vortex core. It is also possible that some of this disturbance is caused by the effect of the vortex flow on the vertical tail. The pilot of the chase aircraft observed that during flights in this region the vortex appeared to be high off the wing and to flow to an area near the tail. Strong vortex flow was observed with no tendency to detach or otherwise produce abrupt flow changes at the maximum combinations of angle of attack and sideslip.

4.2 Lateral-Directional Stability

The lateral-directional behavior of the airplane was examined during the initial flight tests in stages up to 25° angle of attack and 8° (full rudder) sideslip. The vortices remained steady and good directional stability was maintained at 90 knots which was the lowest flight speed tested. Static directional stability data for three airspeeds (180, 130, 100 knots) corresponding to angles of attack of 7°, 12°, and 23° are presented in Figure 5. At 100 knots and full rudder 8° of sideslip was obtained and, as shown in Figure 5, there was little change in stability. It had been anticipated that abrupt changes in lateral-directional responses might result from the changed location, with respect to the leading edge, of the vortex at high sideslip angles. However, both the dihedral effect and sideslip data show a generally smooth variation over the range tested (Fig.5). Although roll-yaw coupling was high, the "Dutch-roll" oscillation was well damped.

The airplane response to a rapid rudder release at 130 knots is shown in Figure 6 and at 100 knots in Figure 7. A summary of the dynamic lateral-directional response is contained in Figure 8. There is little change evident in the period $(P \simeq 3.5$ sec) and damping of the oscillation for angles of attack from 7° to 24°.

The dihedral effect is greater on the Ogee wing airplane than on the basic F5D. The roll motion dominates the "Dutch-roll" mode which is easily excited in mild turbulence. The period is too short for effective pilot damping inputs and the lateral-directional oscillation over the range covered in Figure 5 was unsatisfactory (4-5 Cooper rating) because of the amplitude and acceleration of the roll motion. Although this short-period well-damped high roll-to-yaw motion is unlikely in a large passenger airplane, the pilots felt that the rolling motion would be unsatisfactory from a passenger viewpoint.

4.3 Comparison of Lift, Drag, and Pitching Moment

Flight and full-scale wind-tunnel characteristics of lift, drag, and pitching moment are compared for the unmodified and the Ogee wing F5D airplane in Figure 9. The changes produced by the modification can be evaluated from the wind-tunnel data for each configuration. A small reduction in angle of attack for a given C_L is indicated for the Ogee; however, a large increase in drag reduces the lift/drag ratio in the approach speed range from 5 to about 4. The characteristics of low-aspect-ratio delta wings are evident in the lack of a break in the lift curve and the high induced drag. These data were measured during flight tests[3]. The wind-tunnel data have been corrected for elevon trim angle and the flight data for thrust component.

Ballast and structural limitations prevented flight tests with a more stable center-of-gravity location. Consequently, the stability was neutral to slightly unstable throughout the landing-approach speed range. The flight data curve was faired through scattered data points at the highest lift coefficients because considerable elevon activity was required to maintain steady pitch attitude at airspeeds where there was a marked reduction in control effectiveness (100 knots). Nevertheless, the faired curve reflects the pilot's comments that the airplane has a smooth pitching-moment curve through 25° angle of attack. Abrupt changes in pitching moment did not occur but the level of instability was considered unsatisfactory (Cooper rating 6-7) for instrument approaches and (Cooper rating 5) for visual landings because excessive attention was required of the pilot to maintain pitch attitude at any approach speed. The difference between flight and wind-tunnel data has not been resolved; however, the investigation was primarily concerned with any abrupt changes in stability that are not evident in either measurement.

4.4 Comparison of Low-Speed Handling Qualities

The predominant change in handling qualities produced by the Ogee modification was the excellent directional stability and control which could be maintained to the highest angles of attack evaluated (24°-30°). As a result very little lateral-control-yaw ($N_{\delta a}$) cross coupling was evident at high angles of attack, and the major problem in a (rudder pedals fixed) 45° bank angle turn reversal occurred in pitch rather than yaw control due to the longitudinal instability. Yawing due to lateral control was not a problem. Full rudder sideslips were induced (Fig. 5) at 100 knots without any tendency for the airplane to diverge in yaw even at 25° angle of attack. On (conventional) high-aspect-ratio wings these control actions would create spin entry conditions; however, on this airplane, the control release returns from sideslip were positive and well damped (Figs. 6-7).

In contrast, flight at 15° angle of attack in the unmodified airplane was complicated by the relatively large yawing motions produced by lateral control, and the combined roll-yaw control coupling ($N_{\delta a}$) and dihedral effect resulted in a directional divergence when wings level flight was attempted at 125 knots (gross weight 21,000 lb). At this same weight and airspeed it was not controllable in 30° bank turn reversals because of the large yaw angles induced with rudder pedals fixed and because the airplane tended to diverge in yaw at lower speeds. This characteristic is also typical of extreme angle-of-attack flight in other basic delta-wing aircraft and generally provides the basis for limiting their approach speeds[1]. The most favorable change from the basic F5D effected by the Ogee modification was the elimination of low directional stability and lateral control coupling as factors limiting the selection of approach speeds.

4.5 Ground Effect

The ground-effect measurements made in the 40 by 80 ft wind tunnel are compared in Figure 10 with the flight data. The faired data from the wind tunnel for $C_L = 0.55$ are shown along with data points obtained in flight from $C_L = 0.40$ to $C_L = 0.59$. The flight and wind-tunnel data are in general agreement; however, the faired curves would have been difficult to arrive at with flight data alone. It is seen that 2½° to 3° aircraft nose-up elevon is required to balance the pitching moment due to ground effect from a height of 10 ft to touchdown. A simultaneous increase in C_L occurs as shown in Figure 10. The net result is that the pilots do not notice the moment change since at this height they are applying final flare controls and the additional force required to compensate for the ground effect is insignificant. The increase in trimmed elevon deflections could only be noticed if the pilot were either making an extremely shallow descent to touchdown or descending at a normal rate with elevon controls fixed.

The latter technique resulted in a nose-down rotation of 3° to 4° before ground contact. All landings made with either the Ogee or basic F5D during the test and evaluation period were exceptionally smooth, indicating that the ground-effect characteristics as measured on the Ogee F5D airplane do not create an operational limitation and, in fact, may be a factor in making this airplane easy to land.

5. LANDING-APPROACH-SPEED EVALUATION

The previous sections have been concerned with measuring specific airplane characteristics and evaluating handling qualities. These factors considered together are related to the selection of landing-approach speeds in the following sections.

5.1 Instrument Landing Approaches

Instrument landing approaches conducted on the reverse slope, or "backside" of the power-required curve are some of the most interesting, yet least understood, characteristics of low-aspect-ratio delta airplanes. The degree to which the pilot's workload is increased by the approaches and the criteria which can be applied to this type of operation in order to allow a more accurate prediction of approach speeds were investigated using the Ogee wing F5D-1 airplane. The high induced drag and improved lateral-directional stability and control of the modified airplane allowed test landings to be made at higher values of the reverse slope of the power-required curve than had been evaluated previously.

The flight tests consisted of ILS approaches in a normal terminal area environment under both hooded and actual instrument conditions. Conventional radar vectoring to the ILS outer marker was utilized at a speed 20 knots greater than the final approach speed, which provided a combined task of glide slope interception with a 20-knot airspeed correction. Two nonstandard cockpit instruments were used, vane-driven angle-of-attack and sideslip indicators. The angle-of-attack indicator served the same purpose as a second crewman, providing reference airspeeds as gross weight changed. It also allowed evaluations of very low-speed approaches by providing an easily interpreted indication of the approach angle of attack as compared to the highest angle attained during higher altitude testing.

The landing-approach speeds used for low-aspect-ratio delta aircraft have generally been significantly higher than predicted, and attempts to correlate the pilot selected speeds with various aerodynamic criteria have not been entirely satisfactory. The parameter $(\Delta T/W)$/knot has received some attention as a possible limiting condition for the characteristic "backside" approach condition of low-aspect-ratio delta aircraft. During these tests it was possible to vary $(\Delta T/W)$/knot from -0.001 to -0.005 by varying speed from 120 to 150 knots, as shown in Figure 11.

The airplane was primarily limited in approach speed by the loss of ability to control the flight-path angle while on the reverse slope of the power-required curve and the minimum comfortable approach speeds occurred between 10° and 12° angle of attack where $(\Delta T/W)$/knot varied from -0.0010 to -0.0020. The term "comfortable" is used with reservation because of the poor longitudinal stability throughout the approach-speed range. However, the ability to stabilize and control the flight-path angle was satisfactory in the absence of pilot or turbulence induced pitch attitude disturbances. The reverse slope of the drag curve was evident during the initial 20-knot speed corrections but was not readily detected once the approach speed had been established. Since the airplane had been flown (without precise flight-path-angle control) at angles of attack in excess of 25°, there was little concern with a transient increase in angle of attack or low airspeed during an approach at 10° to 12° angle of attack. Although there were some undesirable aspects of the instrument approaches on the reverse slope of the power-required curve these appeared to be partly offset by the lack of a stall and attendant larger airspeed tolerance.

The slowest ILS approaches (120 knots) were conducted at 1.3 times the minimum airspeed attained with the aircraft during high altitude tests (92 knots). At 15° angle of attack, corresponding to 120 knots, no significant (i.e., felt by the pilot) normal acceleration could be developed with pitch control even as a transient; however, in smooth air, very steady ILS approaches were made easily at this airspeed even though both nose-up and nose-down pitch attitude changes increased the rate of descent and thrust became the only flight-path control. When tight ILS control was maintained, very little notice was taken of the lack of response to up elevon until the last 100 to 200 ft of descent (300-400 ft AGL) on the ILS path where corrections for the displacement errors required more response than was available. A power increase was required to reduce sink rate. On the other hand, the visual portion of the landings (i.e., below 200 ft AGL) was made without difficulty.

At higher instrument approach speeds, the airplane response generally improved and ILS errors became easier to correct. It may not be completely correct to attribute these differences to $(\Delta T/W)/\text{knot}$ since other factors such as changes in dynamic pressure are involved; however, between $(\Delta T/W)/\text{knot} = -0.0025$ and -0.004, approach path control was considered unsatisfactory and could not be recommended for this airplane for instrument conditions. The pilot's comments that at 120 knots (corresponding to $(\Delta T/W)/\text{knot} = -0.004$), transient flight-path angle reductions cannot be attained with elevator control illustrates the limiting conditon.

Although the minimum speed at which the ILS could be flown (Fig.11) occurred at $(\Delta T/W)/\text{knot} = -0.004$, the minimum comfortable speeds occurred between -0.001 and -0.002. It appears that this parameter changes too rapidly with speed to provide a one-value limiting condition; however, the values obtained for comfortable instrument approach speeds could serve as a guide to approach-speed-prediction criteria.

Analysis of closed-loop pilot-vehicle systems has long been considered useful in establishing criteria for predicting landing-approach speed, especially for low-aspect-ratio aircraft[4]. This technique was applied specifically to the Ogee F5D airplane but the analysis was based on aircraft carrier type approaches using a mirror landing system for final approach guidance. The technique appears promising because it includes the complete pilot-airplane loop and therefore should provide a more rational guide than one based on a single parameter. However, as indicated[4], further development is required for this method to be applicable to other types of landings.

The longitudinal stability of the test airplane (Fig.9) was unsatisfactory for the landing approach, especially under instrument conditions, because an inordinate amount of the pilot's attention was required to control pitch attitude, with a consequent neglect of the ILS, check lists, and communications with the approach controller. Although it was possible to decrease the slope of the drag curve by increasing airspeed, the stability remained poor. Alternating flights in the unmodified airplane confirmed that the pilot's workload was reduced in the stable airplane because the airplane would remain trimmed at the approach speed without continuous pitch-attitude adjustments. The pilots indicated that, although increased stability would be required for satisfactory handling qualities, their selection of approach speeds was based on those characteristics which changed with airspeed; therefore, a reduction in the choice of an approach speed would not be expected with an increase in stability. However, the poor stability of the test airplane made it unsatisfactory for instrument approaches under any conditions other than those of the test.

5.2 Visual Circling Approaches

Although the ILS provides a demanding task for approach-speed evaluation, the maneuvering requirements are not large. If the airplane had a reasonably definitive stall, an arbitrary maneuvering acceleration margin could be provided by selecting an approach speed to stall speed ratio (i.e., $V_a = 1.3\ V_s$) . However, since no such simple guide was available, the maneuvering demands of a tight circling approach were also used to evaluate approach-speed limitations. Normally a low visibility circling approach is used to complete a landing on a runway that is different from the primary (ILS) approach runway. The weather minimums for this procedure are a 600 ft ceiling and 1½ miles visibility, which means that a tight turn must be made to keep the runway in sight, and the low altitude of the maneuver demands good flight-path angle control. Bank angles of 30° or more are often required to produce the desired turn radius, and the corresponding normal accelerations reduce the speed margin from stall. Our purpose was to evaluate the characteristics of a nonstalling airplane with a low lift/drag ratio during this type of landing approach.

The first effect noted on the Ogee F5D was the high rate of sink induced by steep bank angles. Attempts to perform 30° level flight turn entries required a large increase in thrust to offset the high induced drag and a pronounced thrust reduction to keep from accelerating rapidly when rolling out of the turn for the landing. Although these characteristics exist on higher aspect ratio aircraft, on the modified F5D they were considered to be severe enough to require at least a 10-knot increase in airspeed for circling approaches over the minimum comfortable speeds selected for ILS approaches. A useful guide used by the pilots in selecting the circling approach speed was to establish the minimum speed at which 45° bank turn reversals could be performed. At 21,000 lb gross weight the speeds for minimum visibility circling approaches were 145 to 155 knots (ILS 135-145 knots).

6. CONCLUDING REMARKS

Flight tests of a delta-wing airplane modified to an Ogee plan form demonstrated that the strong leading-edge vortices which are produced remain steady to over 25° angle of attack and 8° of sideslip and do not adversely affect the dynamic behavior of the airplane. A slight increase in lift-curve slope was obtained by the plan-form change with a sharp leading edge at the expense of higher induced drag. A marked increase in directional stability eliminated lateral-directional control coupling as a low-speed problem; however, the high roll to yaw aspect of the short-period lateral-directional oscillation was unsatisfactory.

The minimum comfortable instrument approach speeds, compared with those for the unmodified airplane, were reduced 10 to 15 knots to 135 to 145 knots ($\alpha = 10^{0}$-12^{0}; $(\Delta T/W)$/knot -0.001 to -0.002) . The approach speeds were limited by a rapid reduction in ability to control the flight path at values of $(\Delta T/W)$/knot between -0.0024 and -0.004, the latter value representing the slowest instrument approaches attempted.

The measured values of nose-down pitching moment and lift increase in ground effect were not observable during routine landings except that subjectively the airplane was exceptionally easy to land at low sink rates.

REFERENCES

1. White, Maurice D., Innis, Robert C. — *A Flight Investigation of the Low-Speed Handling Qualities of a Tailless Delta-Wing Fighter Airplane.* NASA MEMO 4-15-59A, 1959.

2. Werle, Henri, Fiant, Claude — *Water-Tunnel Visualization of the Flow Around the Model of a "Concorde" Type Airplane.* La Recherche Aerospatiale, No.102, pp.3-19, Sept. -Oct. 1964, (A65-13588).

3. Rolls, L.Stewart, et al. — *Flight Investigation of the Aerodynamic Properties of an Ogee Wing.* NASA TN D-3071, 1965.

4. Wasiko, Richard J. — *Application of Approach Speed Criteria Derived from Closed-Loop Pilot-Vehicle Systems Analyses to an Ogee Wing Aircraft.* Systems Technology, Inc., Report No. 141-1(R), 1965

Note: For comments on this paper see page 16.

TABLE I

Dimensional Data for the Test Airplane

	Basic F5D	*Ogee F5D*
Wing area, ft^2	557	661
Wing span, ft	33.5	33.5
Aspect ratio	2.02	1.70
Mean aerodynamic chord, ft	18.25	22.59
Incidence at root, deg	0	0
Geometric twist, deg	0	0
Sweep		
Leading edge at root, deg	52.5	77
Leading edge minimum, deg	52.5	55.8

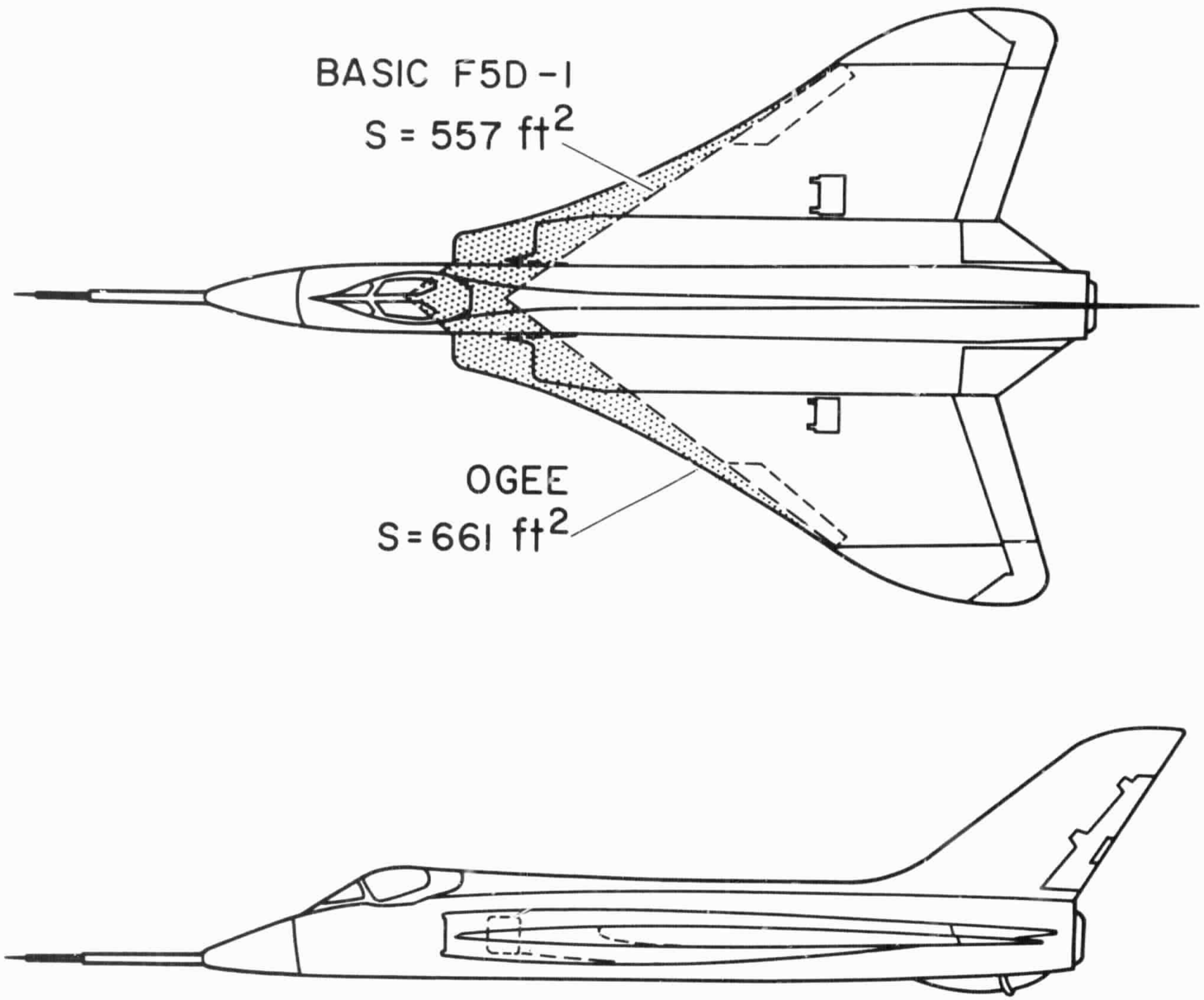

Fig. 1 Test airplane

Fig. 2 Vortex flow on test airplane

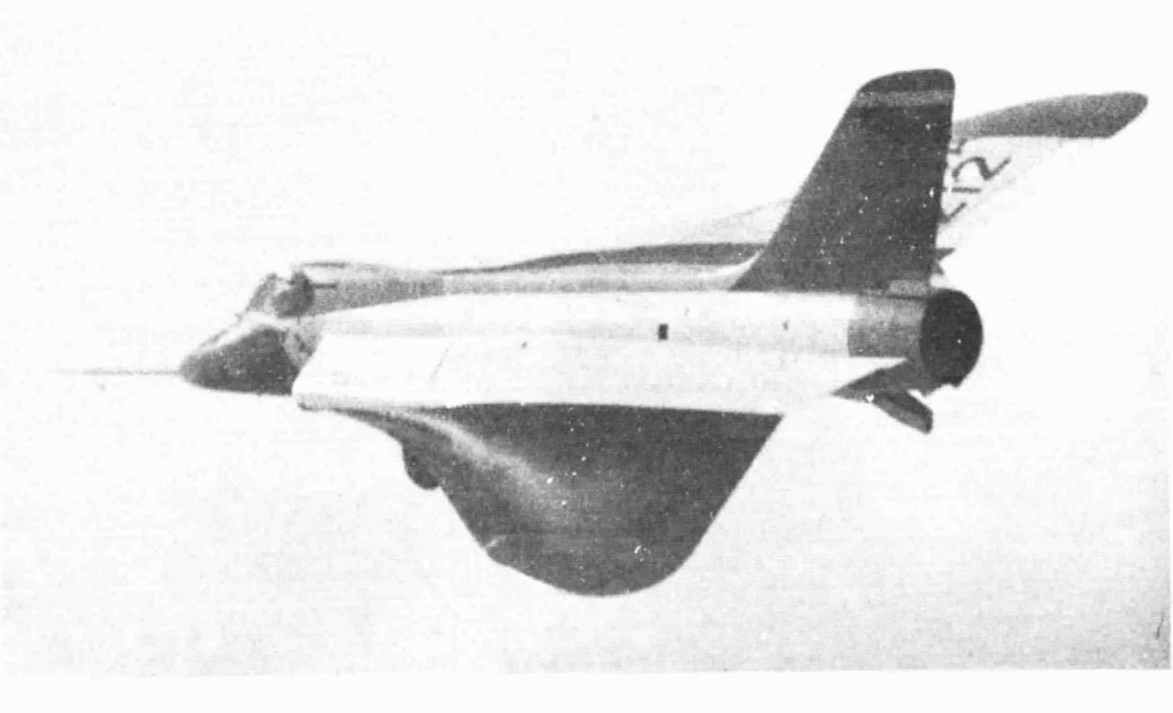

Fig. 3 Photograph of the visible vortex system

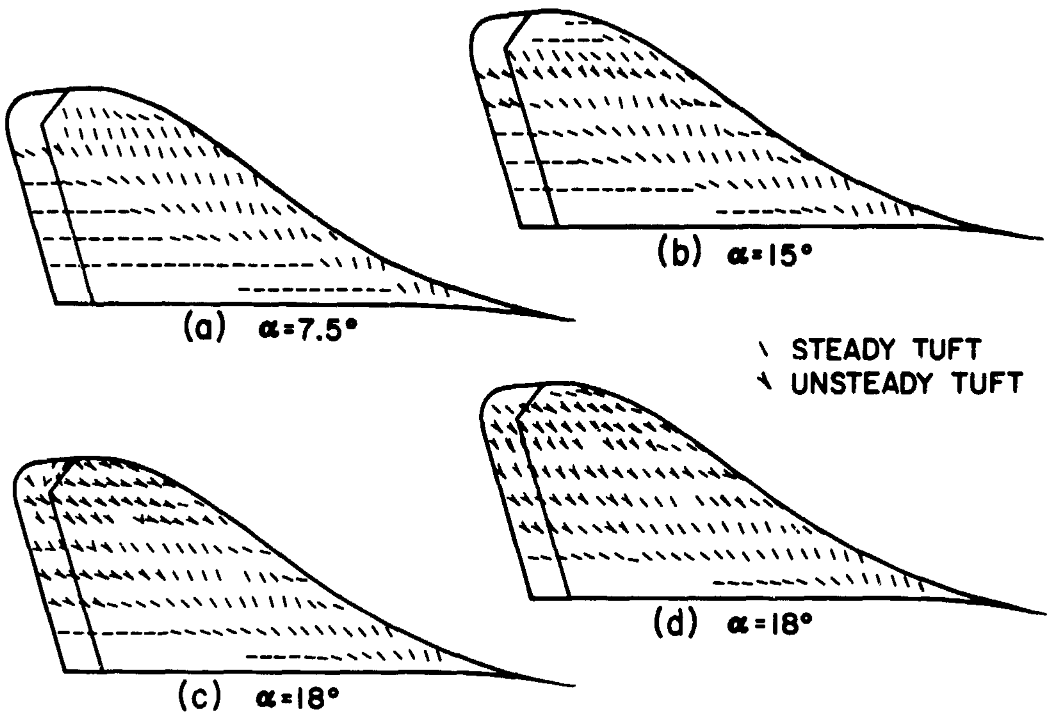

Fig. 4 Wing tuft patterns

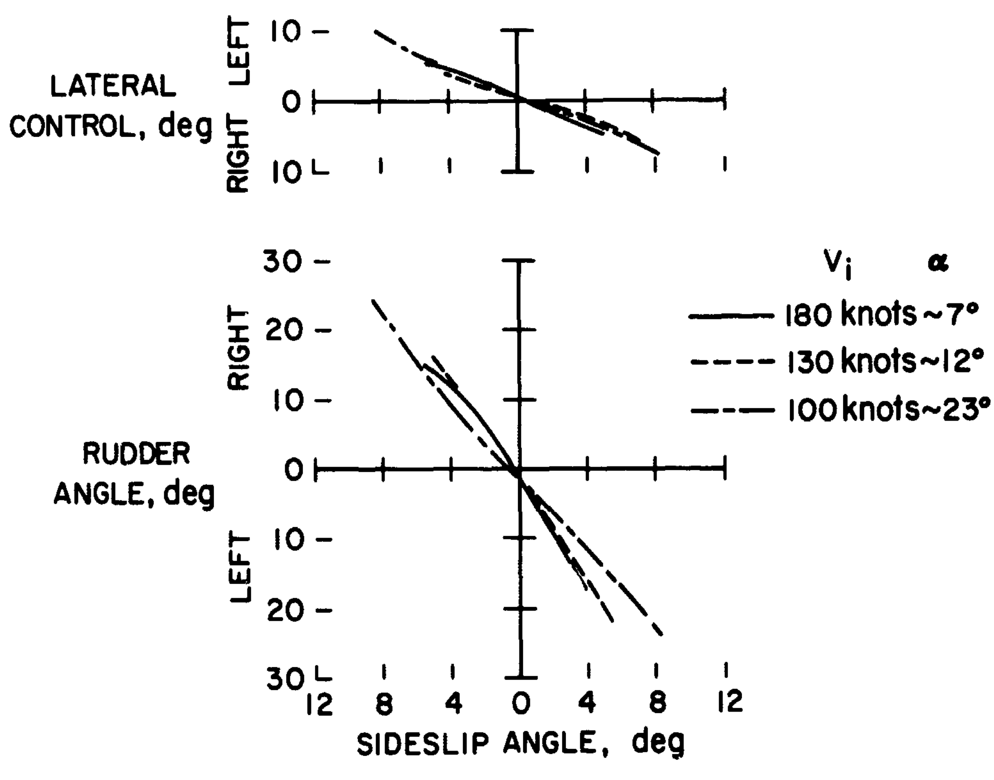

Fig. 5 Static lateral-directional stability

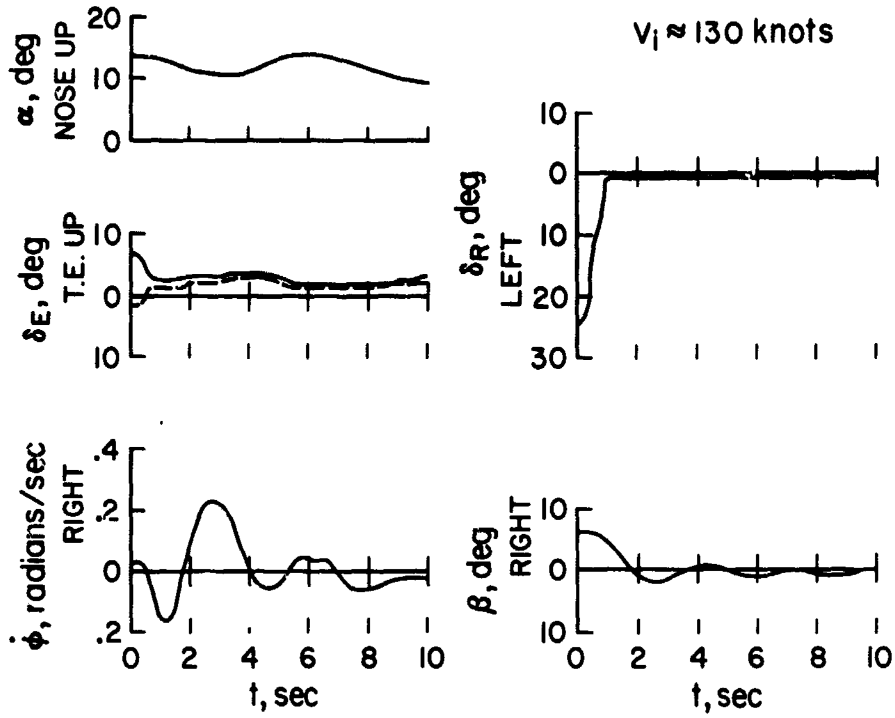

Fig. 6 Lateral-directional oscillation, $V_i \simeq 130$ knots

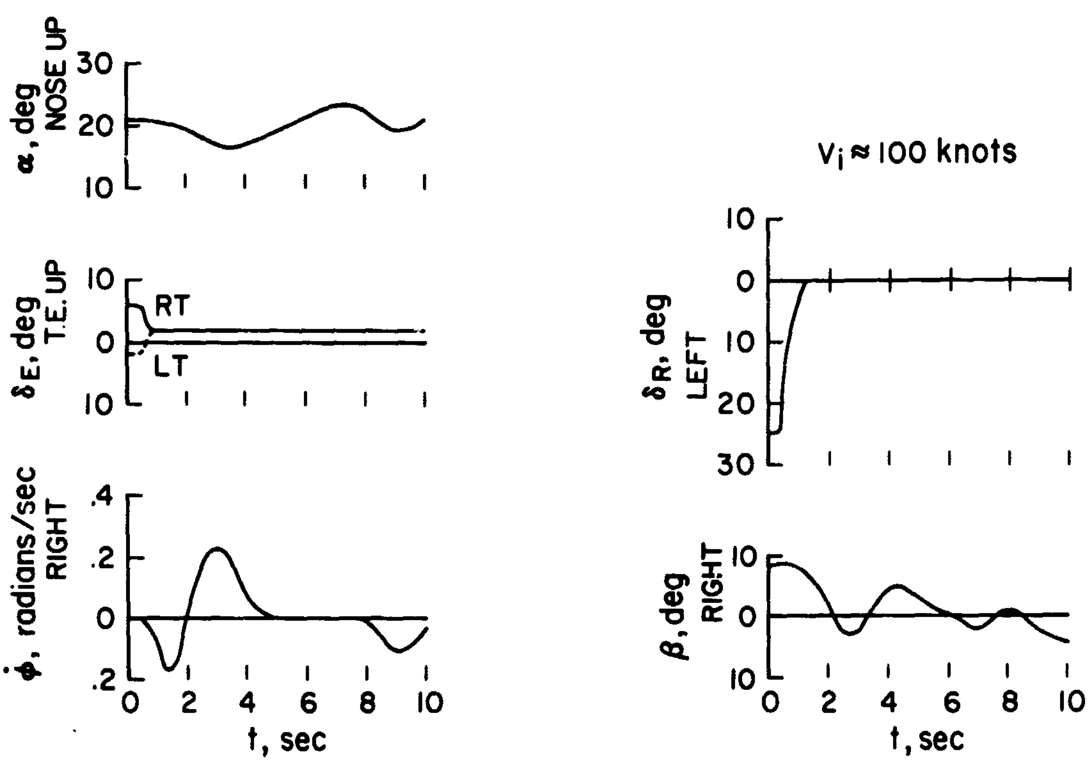

Fig. 7 Lateral-directional oscillation, $V_i \simeq 100$ knots

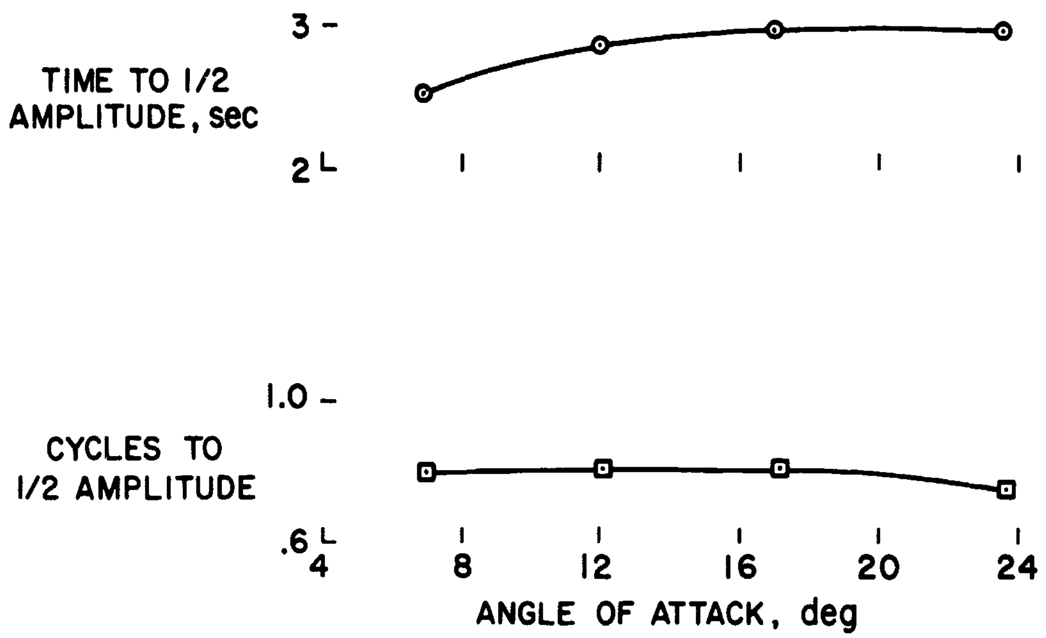

Fig.8 Dutch roll damping characteristics

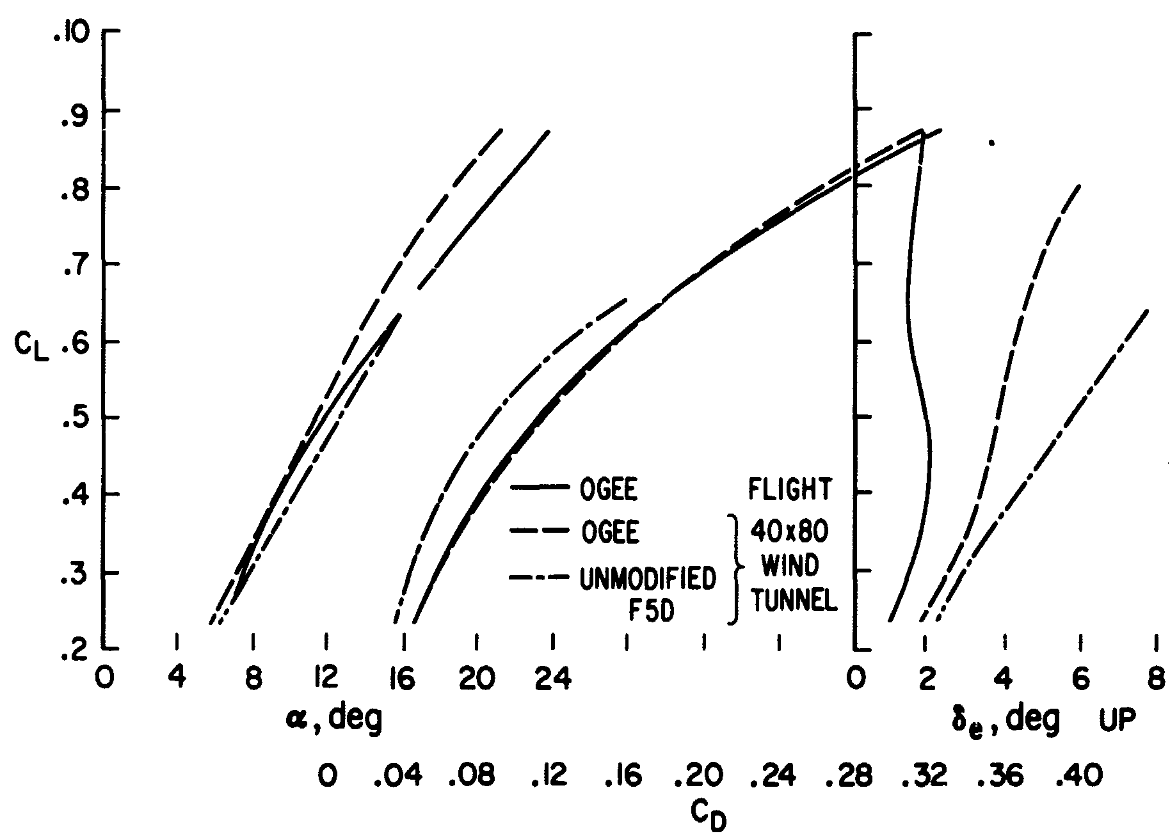

Fig.9 Comparison of lift, drag, and pitching moment

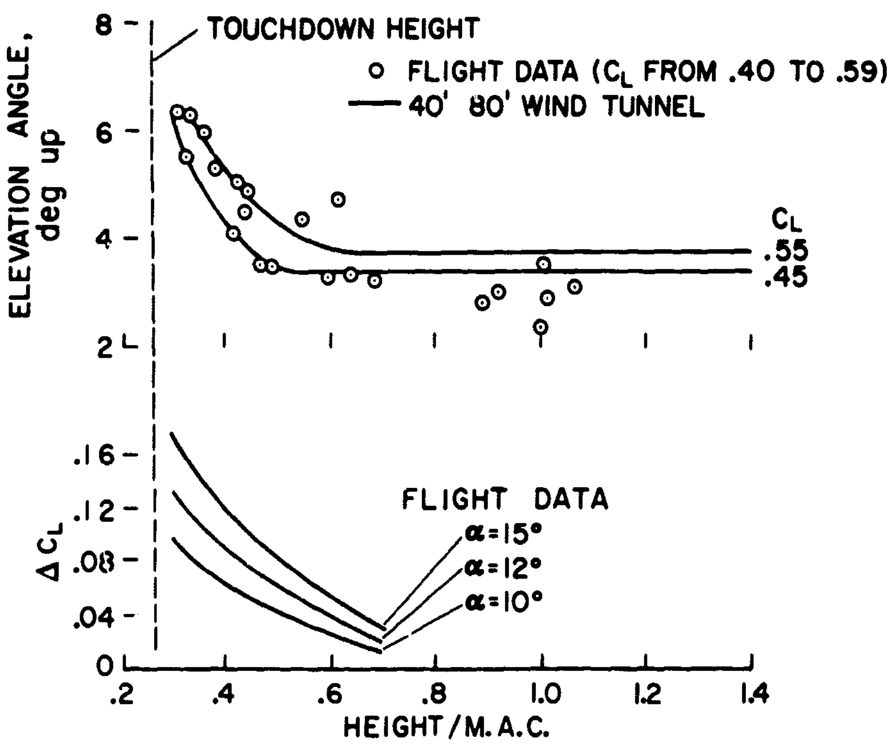

Fig.10 Ground-effect measurements

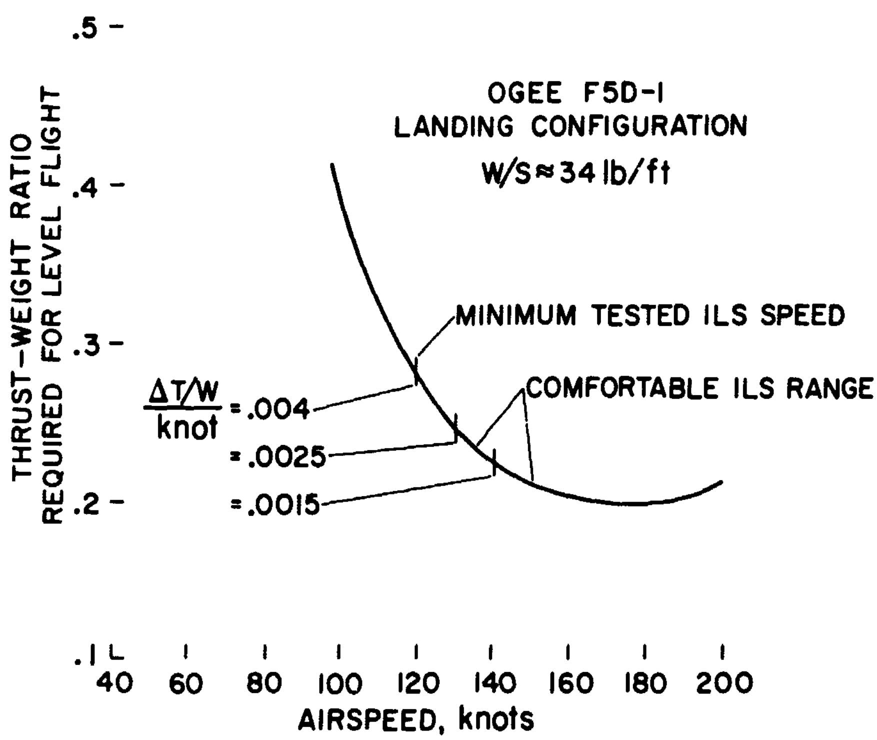

Fig.11 Approach speeds compared to reverse slope of the drag curve.

Comments by M.Ph.Poisson-Quinton, ONERA, France

Correlation of lift data obtained in the wind tunnel on a "Concord" model and in flight on the NASA modified F5D aircraft.

The outline of the sharp leading edge mounted by NASA on the Douglas F5D-1 is very similar to that adopted for the "Concord" supersonic transport aircraft (on the approximate scale of 1/2.5); the shape of the trailing edges is rather different - however, it does not affect directly the development of the vortex lift at high angles of incidence.

It was interesting to compare the data obtained by NASA, both in flight and in the full scale wind tunnel at Ames (Ref.A1) with those provided a few years ago by the ONERA wind tunnel in Cannes on a schematic model of the "Concord" on a scale of 1/24; the wing consisted of a thin plate with a sharp leading edge*, and the longitudinal balance was achieved by means of ailerons set along the whole length of the span.

In the lift curves represented on Figure A1(a), the lift is trimmed in relation to the incidence outside the ground effect; for similar static margins, these curves were obtained, respectively, on the small scale planform of the Concord ($R_e = 1.6 \times 10^6$): and on the modified F5D aircraft, both in flight and in a full-scale wind tunnel ($R_e = 24 \times 10^6$) : there is a good correlation between these three results up to an incidence of approximately 15^o.

Figure A1(b) compares the lift increases obtained while getting close to the ground, at an incidence which is representative of the final approach phase for such an aircraft ($i = 12^o$) : here again, there is a good agreement between the in-flight measurements made by NASA (Ref.A2) and the wind tunnel data obtained in Cannes on the 1/24 scale model of the "Concord", with an adjustable height floor; besides, it had been proved by systematic tests that this testing technique, although questionable for the study of high aspect ratio aircraft, was adequate for tapered wings.

In conclusion, the results of small-scale wind-tunnel tests, performed on a schematic model of the "Concord", correlate well with flight test data obtained on a very similar planform. This good correlation indicates that:

(a) The lift related to the development of vortices on the upper surface of a tapered wing is unaffected by the Reynolds number when the leading edge is thin.

(b) The increase in lift to be expected at take-off and landing is considerable; it is of the order of 30% in the immediate vicinity of the ground.

---

* It should be pointed out that the actual wing of the "Concord" is adapted, by means of a cambered leading edge with a round nose, so as to offer a better maximum lift/drag ratio; therefore, the vortex lift does not appear until a low positive incidence is achieved; then, its development is exactly the same as in the case of a level wing.

REFERENCES

A1.	Rolls, L.S., et al.	*Flight Investigation of the Aerodynamic Properties of an Ogee Wing.* NASA TN D-3071, 1965.
A2.	Rolls, L.S., Koenig, D.G.	*Flight Measured Ground Effect on a Low Aspect-Ratio Ogee Wing, Including a Comparison with Wind-Tunnel Results.* NASA TN D-3431, 1966.

NOTATION

Trimmed $C_Z = C_{L_{TRIM}}$	trimmed lift
$C_{Z\infty}$	lift outside the ground effect
H	height of the centre of gravity above the ground
l_m	mean aerodynamic chord
R_e	Reynolds number

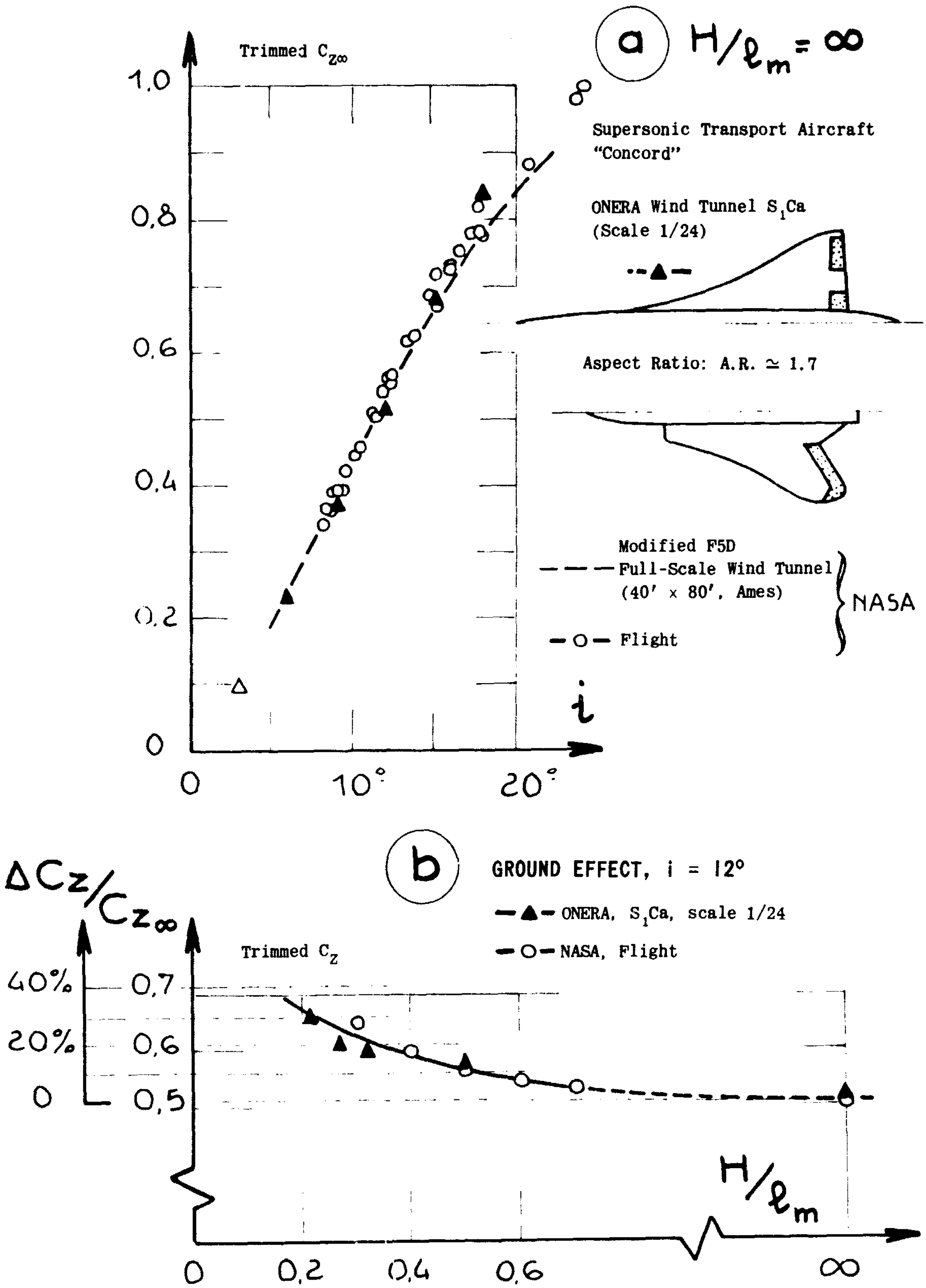
a
H/ℓm = ∞
Trimmed Cz∞
1.0
0.8
0.6
0.4
0.2
0
0
10°
20°
i
Supersonic Transport Aircraft
"Concord"
ONERA Wind Tunnel S1Ca
(Scale 1/24)
Aspect Ratio: A.R. ≃ 1.7
Modified F5D
Full-Scale Wind Tunnel
(40′ x 80′, Ames)
NASA
Flight
b
GROUND EFFECT, i = 12°
ONERA, S1Ca, scale 1/24
NASA, Flight
ΔCz/Cz∞
Trimmed Cz
40%
20%
0
0.7
0.6
0.5
H/ℓm
0
0.2
0.4
0.6
∞

Figure A1